Impact constraints on the age and origin of the lowlands of Mars

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Received 25 August 2005; revised 8 December 2005; accepted 15 December 2005; published 4 March 2006.

[1] Visible and buried impact basins, seen as "Quasi-Circular Depressions" (QCDs) in MOLA data, provide important new constraints on the age of the Martian lowlands. The buried lowlands are no younger than Early Noachian, at least as old as the oldest exposed (visible) surface units in the highlands. A model absolute age for these buried lowlands is 4.04–4.11 GY (or earlier) but similar model ages for the largest lowland basins are older yet, 4.08–4.18 GY. The lowland crust both formed and became low no later than 500 million years after Mars formed, and likely even earlier. This constrains models for the origin of the fundamental crustal topographic dichotomy on Mars. Mechanisms which operated both early and quickly during the earliest history of Mars (e.g., large impacts) may be more likely than those requiring extended periods of time (i.e., endogenic models). **Citation:** Frey, H. V. (2006), Impact constraints on the age and origin of the lowlands of Mars, *Geophys. Res. Lett.*, *33*, L08S02, doi:10.1029/2005GL024484.

1. Introduction

[2] Origin of the fundamental crustal dichotomy (lower, thinner and apparently younger crust in the northern lowlands) on Mars remains a major controversy. Endogenic [*Wise et al.*, 1979; *McGill and Dimitriou*, 1990; *Sleep*, 1994; *Zhong and Zuber*, 2001; *Lenardic et al.*, 2004; *Roberts and Zhong*, 2004] and exogenic [*Wilhelms and Squyres*, 1984; *Frey and Schultz*, 1988, 1990; *Frey*, 2003] processes have been invoked to explain these hemispheric-scale differences. There is no direct observational evidence that uniquely supports endogenic processes, which were originally based on the apparent age difference between the lowlands and highlands. By contrast, there is growing evidence for very large impacts on Mars. If these are the cause of the low northern elevations, then the younger surface ages there do not represent the original age of the lowland crust, but rather resurfacing of an older crust [e.g., *Tanaka et al.*, 2003].

[3] MOLA data have revealed a large population of "Quasi-Circular Depressions" (QCDs) on Mars [*Frey et al.*, 1999, 2002; *Frey*, 2006]. Many QCDs are visible impact craters in various stages of preservation; many more have no visible structure. These have been interpreted to be buried impact craters [*Frey et al.*, 2002; *Frey*, 2003; *Frey*, 2006; *Buczkowski et al.*, 2005]. If true, total population crater counts based on both visible and buried features provide the most complete record of crater retention for a given area. Such counts suggest the lowland crust below the plains is significantly older than previously thought.

2. Crater Retention Ages of the Highlands and Lowlands

[4] In our original study [*Frey et al.*, 2002], QCDs > 50 km diameter were mapped in the lowlands using early MOLA data (32 pixels/degree). Figure 1a shows the total population lowlands curve (blue) compared with total population counts for a large area of the central highlands of Mars ("Arabia"). Also shown are visible and total population counts for the oldest exposed surface unit on Mars, the Early Noachian Nh_1 unit SE of Hellas [*Frey and Frey*, 2002; *Frey et al.*, 2002; E. L. Frey, unpublished data]. All follow a -2 power law slope when the statistics become good enough. The total lowland population lies along the same -2 trend as the visible Nh_1, but below the total (visible + buried) Nh_1 and "Arabia" curves. Thus the total lowland crater retention age (CRA) is similar to that of exposed highland surface units of Early Noachian age, though somewhat younger than the true age of the highlands.

[5] This result was confirmed by a global study of QCDs > 200 km diameter [*Frey*, 2003, 2004, 2006], which include some very large (D > 1000 km) basins such as Hellas, Argyre and Isidis in the highlands as well as Chryse, Acidalia and the now well-accepted Utopia in the lowlands [*Schultz and Glicken*, 1979; *Schultz et al.*, 1982; *McGill*, 1989; *Schultz and Frey*, 1990; *Stockman and Frey*, 1995]. Figure 1b shows cumulative frequency curves for these large QCDs. Very large (mostly visible) basins follow a -2 power law slope but the visible population shows a significant depletion at D < 1300 km before recovering the -2 trend at D < 600 km. This depletion may represent a major, global scale resurfacing event, perhaps the formation of the lowlands [*Frey*, 2003, 2004, 2006]. The buried highlands and buried and total lowlands do not show this depletion. At D < $\sim$500 km the buried and total population lowlands plot above the visible highlands, indicating the (average) lowland crust is older than the (average) exposed highland surface, but still younger than both the buried and total highland populations.

[6] Figure 1c compares the two studies, and adds -2 power law extrapolations of major stratigraphic boundaries based on *Tanaka* [1986]. Within their errors, the two lowland curves coincide. Both lie well into the Early Noachian, confirming this as the (minimum) age for the crust below the plains. The N(200) CRA for the lowlands is $\sim$2.5.

3. Model Absolute Ages

[7] The average CRAs place the lowlands in a relative stratigraphic time scale, but do not provide "absolute ages". Absolute ages are important for connection to numerical models, but cannot be determined in the absence of documented rock samples. N(200) relative CRAs can be converted into model "absolute" ages [*Frey*, 2004, 2006] using

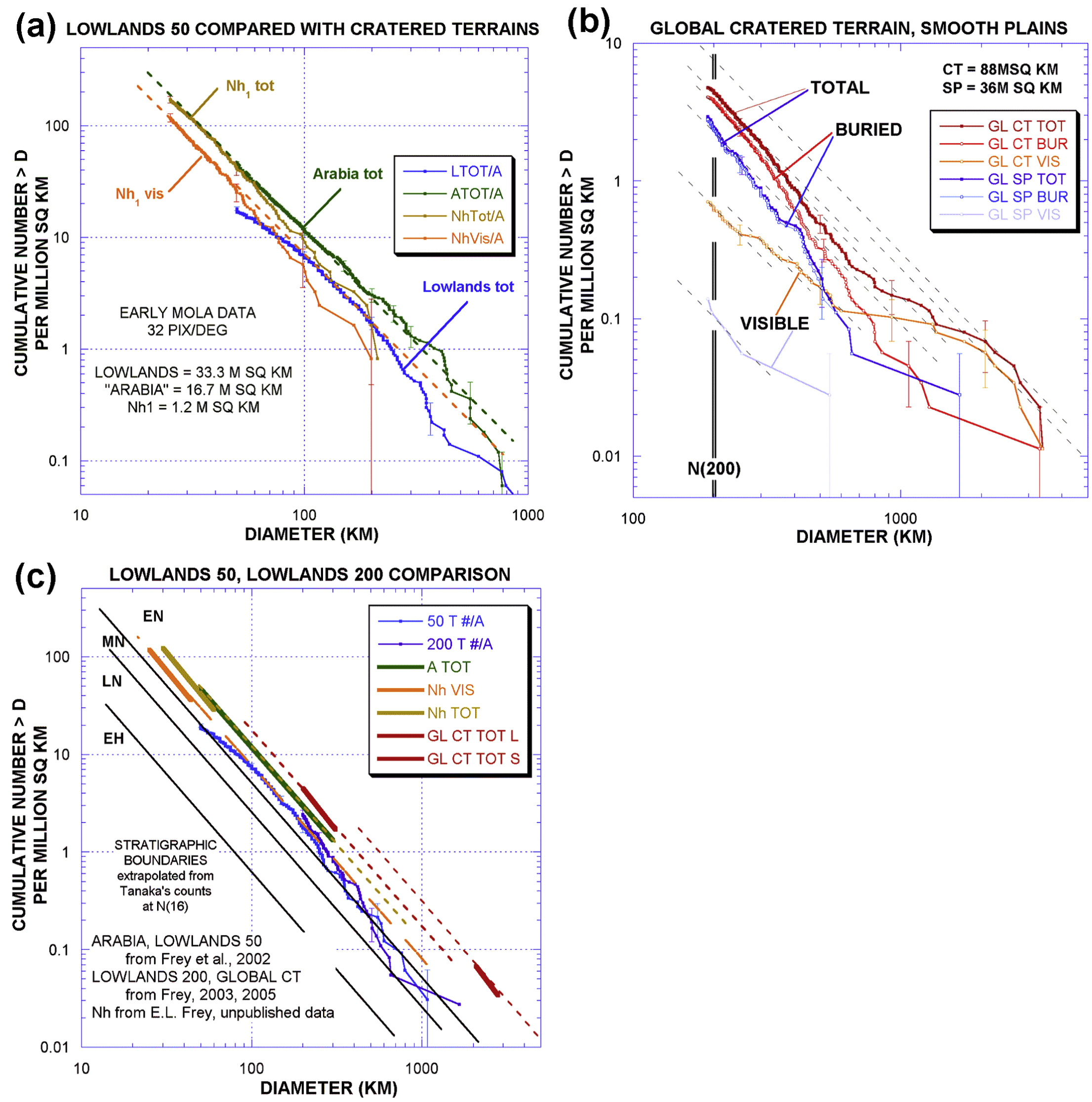

Figure 1. Cumulative frequency curves for highlands and lowlands from two separate studies. (a) Original study where QCDs > 50 km diameter in the lowlands were compared with a large area in the central highlands ("Arabia") [*E. L. Frey et al.*, 2002] and also with the oldest (early Noachian) exposed surface unit, Nh_1, SE of Hellas (E. L. Frey, unpublished data). All curves follow a −2 power law trend over some diameters, and the lowlands lie along the same trend as the visible Nh_1 population in SE Hellas. This suggests the lowlands are about the same age as the oldest exposed (visible) Early Noachian surface unit, but still somewhat younger than the total population age for these and the Arabian highlands. (b) Lowlands and highlands from a global study of QCDs > 200 km diameter [*Frey*, 2003, 2006]. Over the entire diameter range, lowlands are younger than the highlands (based on total population age), and are older than the visible highlands (for D < 500 km diameter). (c) Total population lowland curves from the two studies. Within their errors, the two curves coincide, follow the same age trend as the oldest visible highland units but are younger than the highlands overall, and suggest an average N(100) age of about 10 ± 1 for the lowlands.

the Hartmann–Neukum (H–N) model chronology [*Hartmann and Neukum*, 2001]. Details are provided in Figure 2. There are two important caveats: (1) The H–N timescale is uncertain by probably a factor 2 (W. K. Hartmann, personal communication, 2002). (2) All the buried and total N(200) ages shown are likely too low, because additional basins certainly exist that are so deeply buried that they retain no relic topographic relief and cannot be seen as QCDs in MOLA data.

[8] From Figure 2 the lowlands have a total H–N age of ~4.075 ± 0.035 GY. The largest basins in the lowlands, in which many of these QCDs are located, are older, as they should be, with a model age of 4.13 ± 0.05 GY. These are both older than the visible highlands (3.79 GY), but younger than the buried (4.18 ± 0.07 GY) and total highlands (4.23 ± 0.09 GY).

4. Implications for the Origin of the Crustal Dichotomy

[9] Unless there is some way to preserve the large population of superimposed Early Noachian (now buried) impact craters while lowering the crust, the lowland crust not only formed in the Early Noachian but also became low

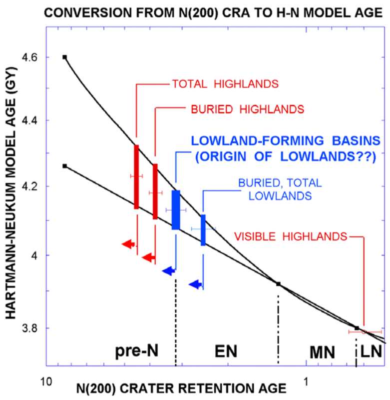

Figure 2. Conversion from N(200) crater retention ages (CRAs) to *Hartmann and Neukum* [2001] (H-N) model ages. N(200) ages for stratigraphic boundaries based on −2 power law extrapolation of *Tanaka*'s [1986] counts at smaller diameters. For times earlier than the Early Noachian/Middle Noachian boundary, we assume two cases: the earliest N(200) age we find (a −2 power law extrapolation to D = 200 km from the largest diameter basins in Figure 1b) is either 4.6 GY (the origin of Mars, therefore a maximum age) or 4.26 GY, a linear extrapolation from the H-N ages for the stratigraphic boundaries (likely a minimum age). Vertical bars show possible range of ages for a given N(200). Formal counting errors shown on N(200) ages. See text for details.

during that time [*Frey*, 2003, 2006; *Frey et al.*, 2002]. Certainly most of the lowland crust has been low since the formation of the three largest lowland basins (Chryse, Acidalia, Utopia), if not before. The chronology in Figure 2 suggests there could have been perhaps 0.47 ± 0.05 GY between the formation of Mars and the Utopia impact, though likely less (as the true age of Utopia is probably older than shown). These very old ages may help constrain the processes by which the lowlands could have formed, and certainly favor processes which operated early and quickly in Martian history.

[10] It may be hard to form the lowlands by endogenic processes in the short (model) time available. Most mechanisms previously suggested [e.g., *Sleep*, 1994; *Zhong and Zuber*, 2001] take hundreds of millions of years and result in a relatively late formation of the lowlands (Late Noachian-Early Hesperian [e.g., *McGill and Dimitriou*, 1990]). For example, *Zhong and Zuber* [2001] were able, by employing a very steep viscosity gradient, to generate a degree-1 mantle convection pattern after 400 million years. While this appears to fit within the possible time span between the formation of Mars and the latest formation of the lowlands, a still unknown and still unmodeled [*Roberts and Zhong*, 2004] but likely long time is still required to reduce the topography by several kilometers [*Frey et al.*, 1998]. If the highland crust is at all younger than the age of Mars (as the QCD data suggest) and/or the largest lowland basins are any older than indicated by the N(200) ages (quite likely), there is even less time available.

[11] By contrast, the largest lowland QCDs (Utopia, Acidalia, Chryse) do account for much (but not all) of the present lowland topography and their formation by impact offers a simple, well-understood, essentially "instantaneous" mechanism for an early formation of both low topography and thin crust [*Frey*, 2003, 2006]. Certainly these areas have been low (and thin) since the Chryse, Acidalia and Utopia impacts occurred. We cannot rule out the possibility that these impacts formed on and modified pre-existing lowland crust formed by some endogenic process [*Nimmo and Tanaka*, 2006], but this would require that such processes occurred even earlier and had established such a lowland prior to the impacts.

5. Discussion

[12] The above age constraint is an average over the entire lowlands. It is of interest to know if different parts of the lowlands have different ages, which might indicate either different processes or a process that operated at different times in different places. We have begun a number of regional scale (2–3 million km^2) studies to determine the CRAs within the lowlands and compare that with the average CRA for the lowlands as a whole (~33 million km^2). Two different portions of Utopia [*DeSoto and Frey*, 2005; Fristad, unpublished data, 2005] and regions to the SE [*Frey et al.*, 2005; R. M. Lazrus, unpublished data, 2004, 2005] and NW of Acidalia (Fristad, unpublished data, 2005) all have N(100) ~ 10 (±1),essentially the same as the average N(100) age for the lowlands extrapolated from the N(200) age described above. We note these studies were done by three different individuals; the similarity in total population age is remarkable, and suggests much of the lowlands probably formed at the same time. Amazonis is notably younger, and differs on its eastern and western halves. The eastern portion lacks many buried QCDs, probably because the area is overlain by thick and young lava flows. In W Amazonis, knobs outline many partially buried craters which contribute to the visible QCD population and there is an appreciable buried population, but the total population still has an N(100) age only half that of the other regions studied. While "lowlands" in relief, Amazonis differs from the other regions in geology [*Tanaka et al.*, 2005], exposure of partially buried craters (described above), crustal thickness (thicker than other parts of the lowlands [see *Neumann et al.*, 2004]), and in crater retention age (younger than other areas). It is also the largest region of lowlands not associated with a very large QCD like Utopia, Acidalia or Chryse.

6. Conclusions

[13] We see in QCDs clear evidence for a cratering history earlier than the oldest visible highland surface units [*Frey and Frey*, 2002], a "pre-Noachian" [*Frey et al.*, 2002; *Frey*, 2003] that, based on *Hartmann and Neukum* [2001] model ages, includes recoverable information hundreds of millions of years prior to that visible at the surface [*Frey*, 2004, 2006]. The buried lowlands, below the smooth plains, are substantially older than previously thought: most lowland crust is Early Noachian in age, with N(200) ~ 2.5, or 4.075 ± 0.035 GY in a *Hartmann and Neukum* [2001] chronology. The three largest lowland basins are older yet, with N(200) ~ 3–3.2 and a H–N age of 4.13 ± 0.05 GY.

Because the N(200) ages derived from QCDs are minimum crater retention ages, the lowland crust is likely even older.

[14] While we cannot rule out that lowlands may have existed before and then been modified by these largest lowland impacts [e.g., *Nimmo and Tanaka*, 2006], it is clear that lowlands must have been present in these areas following them. We take N(200) $\sim$ 3–3.2 to be the youngest possible age of the formation of the crustal dichotomy, but note that it could have been even earlier. We also suggest this defines a convenient boundary between Early Noachian and "pre-Noachian" time [*Frey et al.*, 2002; *Frey*, 2004, 2006], a designation recently adopted in geologic mapping of the northern lowlands [see *Tanaka et al.*, 2005]. This is also close to the time when the global magnetic field died, based on which basins do and do not have anomalies within their main rings [*Frey*, 2003, 2004, 2006]. It appears N(200) $\sim$ 3–3.2 ($\sim$4.13 GYA?) was an important time in early Martian history.

[15] Time available for endogenic processes to produce lowlands is short compared with what most current models require. While degree-1 mantle convection appears feasible if extreme conditions are invoked, to date no models have provided a time scale for the second half of the problem: actually lowering the topography by 3–5 km before this is accomplished by Utopia-size impact events. There is no unique observational evidence for such internal processes whereas increasing evidence for large and ancient impacts has emerged. The early formation of the lowland crust, and its apparent low elevation for most of Martian history, favor processes which operated both early and quickly, a hallmark of impact events.

[16] **Acknowledgment.** The author thanks the organizers of the "Hemispheres Apart" workshop in fall 2004, which gave rise to this paper, and to the important contribution of a reviewer who properly noted the limitations of the information presented here.

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